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On the Design of Human-Safe Robot Manipulators

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1. Introduction

Bringing robot manipulators in the same environment as humans seems a natural evolution in the path towards more advanced robotics. This upcoming co-existence will offer a tremendous potential to improve many industrial applications such as manufacturing and assembly. In this paradigm, an efficient synergy between human and robot can be obtained by combining the human's reasoning ability and adaptability in unstructured environments with the inexhaustible strength of robots.

The current generation of commercially available robot manipulators is not designed to fit the specific needs required by this novel collaboration. Indeed, control algorithms that enable an intuitive and efficient interaction between humans and robots are still missing to industrial robots. At an even more fundamental level, the way they are currently designed presents significant risks in the proximity of humans. Many studies have investigated this last aspect to demonstrate the potential danger of a robot Zinn, Khatib, Roth & Salisbury (2004a) and to understand and provide metrics to characterize to the level of this threat Haddadin, Albu-Schaffer, Frommberger & Hirzinger (2008); Haddadin, Albu-Schaffer & Hirzinger (2008); Yamada et al. (1997). The next step for robot designers should focus on increasing human safety to an acceptable level according to the conclusion of these studies.

The aim of this chapter is to present how, at the conceptual level, robot manipulators should be mechanically designed to be harmless for humans. Both established and novel concepts will be reviewed to provide actual guidelines to the robot designer. Serial elastic actuators (SAE), distributed macro-mini (DM2) and variable stiffness joints will be reviewed whereas more emphasis will be placed on force limiting devices (FLD), robot soft covering and a method for efficiently coupling robot joint actuators for reducing their potential of transferring energy to the surrounding environment.

2. Review

To build safe and dependable robots, engineers and researchers are using three different strategies:

1. to develop algorithms that use vision systems or proximity sensors to *anticipate* and *avoid* potentially harmful contacts Ebert et al. (2005); Lu et al. (2005);

2. to *detect* a collision by monitoring joint torques or a robot skin and quickly *react* to maintain the contact forces under a certain levelDe Luca et al. (2006); Duchaine, Lauzier, Baril, Lacasse & Gosselin (2009);
3. to *design* robots that are *intrinsically safe*, *i.e.*, that are physically unable to hurt a personChoi et al. (2008); Kim et al. (2007); Park et al. (2009; 2008); Sardellitti et al. (2007); Tonietti et al. (2005); Zinn, Khatib & Roth (2004).

It is clear that the *avoidance*, *reaction* and *design* strategies can be combined together to create safer and more dependable robots. However, the first two options alone cannot fully guarantee human safety. This can be explained by considering that a robot intended to interact physically with a person will require the ability to distinguish between desirable and undesirable contacts (or *good* and *bad* contacts). This can be done either by disabling safety sensors on the robot parts intended to interact or by running an algorithm that will decide if the upcoming contacts are desirable or not. In either case, safety is compromised either by unprotecting certain parts of the manipulator or by giving the robot some sort of 'judgment capability' which, even in the case of the human, is condemned to occasionally be wrong. Furthermore, the *avoidance* and *reaction* strategies rely on electronic components that can fail. Finally, one could argue that an operator would feel insecure working with a powerful machine with his safety guaranteed only by an algorithm. It can thus be concluded that the only way to obtain *safe* and *dependable* robots is to use the *design* strategy, which leads to the development of robots that are *intrinsically safe*.

2.1 Series Elastic Actuators (SEA)

To create *intrinsically safe* robots, the usual approach is to make them compliant. Indeed, compliance reduces the peak force attained during a collision. By extending the duration of the contact, it also allows the controller to sense it and react to reduce potential damages, under certain constraints (*i.e.*, reaction time). One early technique Pratt & Williamson (1995) to create compliant robots consists in placing the actuators of a serial robot at its base and linking them to the joints with an elastic transmission. However, the resulting *Series Elastic Actuators* (SEA) also limit the precision and stiffness of the robot. Moreover, as stated by the authors of Pratt & Williamson (1995), compliant joints can store potential energy. It can be argued that this energy could be harmful if released in an uncontrolled manner. Thus, a compromise must be achieved between safety and performance. The following sections present publications that propose solutions to increase safety while maintaining precision as much as possible.

2.2 Active Compliance

Active compliance Hogan (1987); Salisbury (1980) is a technique in which a regular robot is controlled to present a compliant interface at its effector. In a certain way, this technique is the ancestor of admittance control: efforts are measured at the effector and processed to command a displacement equal to the contact force divided by a virtual spring stiffness. Thus, the robot behaves like a spring around its trajectory and the compliance can be adapted online to match variable safety requirements. Unfortunatly, the response time of traditional actuators is longer than what is required to accommodate high frequency forces applied during collisions. Consequently, during a collision, the robot does not have a compliant behaviour and thus this technique is not suitable for the design of safe robots.

2.3 Programmable Passive Compliance

Programmable Passive Compliance Choi et al. (2008); Kim et al. (2007); Tonietti et al. (2005); Wolf & Hirzinger (2008) consists in using a compliant joint for each axis of the robot and a second set of actuators that allow the adjustment of each joint stiffness. This is obtained either by using two antagonistic actuators or by having a second actuator that adjusts the stiffness via a mechanism. This technique allows high stiffness (precision) at low velocity in addition to low stiffness (safety) at high velocity, *i.e.* when the manipulator is usually dangerous. This gives the controller the ability to continuously adjust the compromise between safety and performance. However, these characteristics are obtained by adding weight and complexity to the manipulator. Also, for the mechanisms currently proposed in the literature, the ratio between the largest and lowest stiffnesses is not sufficient to obtain high precision — by manufacturing standards — at low velocity, when collisions are less dangerous.

2.4 Distributed Macro-Mini Actuation (DM^2)

Distributed Macro-Mini Actuation (DM^2) Zinn, Khatib & Roth (2004), developed at Standford University, consists in actuating each joint with two actuators in parallel. The *macro* actuator is powerful but has a limited bandwidth. It is located at the base (to reduce inertia) and actuates the joint via an elastic cable transmission unable to transmit high frequency forces, characteristic of a collision. The *mini* actuator is directly located at the joint and has a large bandwidth. However, its size prevents the transmission of high torques, which makes the robot safer during collisions. The result is a combination of a large actuator that supplies large static torques, such as the ones induced by the robot's weight, and a smaller one that compensates for high frequency perturbations. In practice, this technique seems difficult to implement because it adds complexity to the manipulator's design, especially by doubling the number of required actuators. Recent developments Sardellitti et al. (2007) use two antagonistic pneumatic muscles as the *macro* actuator.

2.5 Nonlinear Passive Compliance

It has recently been proposed Park et al. (2009; 2008) to place on each joint a mechanism whose compliance varies by purely mechanical means. It is composed of two disks linked by a force transmitting pin and two mechanisms, each comprising two bars, one slider and one preloaded spring. In a normal situation, the force in the spring prevents the mechanism from moving. When the transmitted torque exceeds the threshold, the initial spring force is overcome and the mechanism starts moving in the slider. As the mechanism moves, the transmitted torque is reduced by the linkage geometry, even if the spring force is increased. The result is a rigid mechanism that becomes highly compliant when the transmitted torque exceeds a threshold that depends on the design parameters. Thus, the mechanism acts like a torque limiter (or a clutch) until the slider hits the end stop.

This is an interesting solution since by placing such torque limiter in series with each actuator, the resulting manipulator will be rigid unless external forces applied on it exceed a certain threshold, in which case it will become compliant and safer. This technique allows the design of robots that are stiff and accurate under normal conditions, but safer when collisions occur. Moreover, this principle is realized mechanically, which means that the reliability of this safety system does not depend on electronic components. Also, the mechanism is simple, compact and light. For all these reasons, nonlinear passive compliance is a promising approach.

However, this method also has some disadvantages. First, by adding a torque limiter on each joint of a serial robot, the force threshold will depend on the configuration of the manipulator.

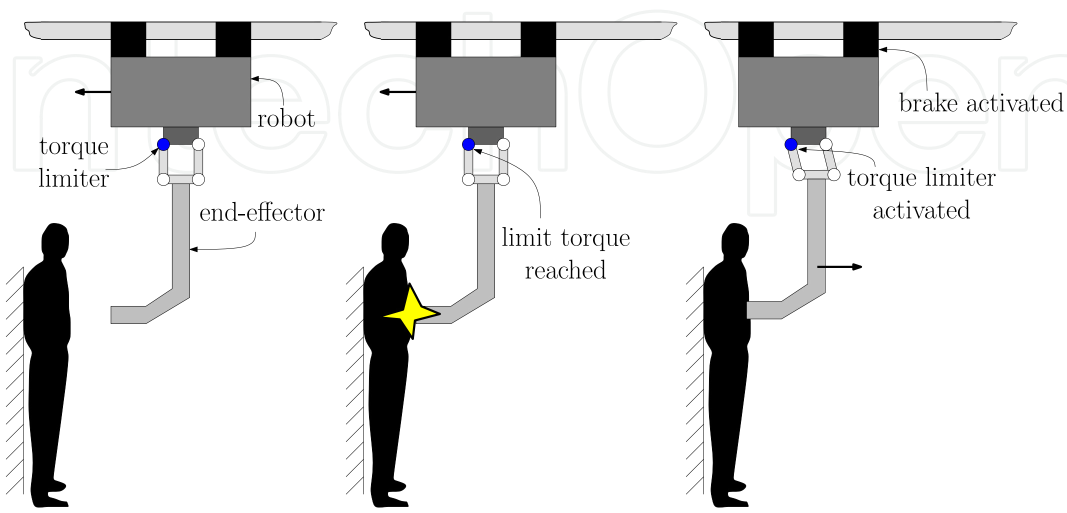
This is because the relation between external forces and articular torques is determined by the Jacobian matrix of the manipulator, which is a function of the manipulator's pose. The threshold will also depend on the contact location and on the force orientation, which is not desirable since it means that the safety level will vary throughout the robot's external surface. Moreover, a manipulator in a singular configuration could theoretically apply infinite forces in certain directions that would not induce any articular torque. These issues arise from the articular architecture of the safety mechanism and consequently a mechanism using torque limiters in a Cartesian architecture would circumvent them and offer the same safety level, regardless of the manipulator's configuration.

Some Cartesian safety devices already exist. One of them Park et al. (2007) was developed by the same researchers as the previously mentioned torque limiter. In this case, the slider-spring mechanism is packaged in the robot's last member, allowing the end-effector to become compliant if a collision induces a large moment relative to the mechanism. The other one is a commercial product *Collision Sensor for Robotic Safety - Robotic Crash Sensors from ATI* (n.d.) that is mainly used to protect a tool if an unexpected contact occurs. These devices, however, possess disadvantages similar to those of the articular mechanisms. Since they are sensitive to external moments, the force threshold depends on the contact orientation and location on the end-effector. Therefore, they are reliable only when collisions occur at a pre-determined location, which is not the case in general for large end-effectors in an uncontrolled environment.

3. Cartesian Force Limiting Devices

A technique that combines torque limiters with parallel mechanisms to create Cartesian force limiting devices (CFLD) was recently proposed in Lauzier et al. (2009). The device behaves like a structure unless the external forces exceed a certain threshold, leading to the activation of one or more degree of freedom. If the parallel mechanism performs pure translation motions, replacing the actuators with torque limiters results in a CFLD that is sensitive to forces – not moments – and thus the threshold is independent from the location of the force application point. Cartesian force limiting devices are particularly well suited for ceiling-suspended robots because their end-effector is the only part on which a collision can occur. During a collision, the motion of the end-effector can thus be decoupled from the rest of the robot if a CFLD is placed between them.

Fig. 1 shows an example of a simple 1-DOF CFLD mounted between a suspended robot and its end-effector. The mechanism is a parallelogram linkage in which one revolute joint was replaced with a torque limiter. Under normal conditions, the torque limiter prevents the mechanism from moving and thus the end-effector is fixed rigidly to the robot. However, if a collision occurs, the couple passing through the torque limiter becomes too high and the mechanism is allowed to move, as shown in the middle and right pictures. This practically "disconnects" the end-effector from the robot and thus the person involved in the collision is only subjected to the inertia of the end-effector, which can be significantly lower than the inertia of the whole robot. For the mechanism to be effective in increasing the safety level, the collision has to be detected and the robot must stop before the mechanism reaches the end of its travel. The collision can be detected with a limit switch placed on one of the links and an emergency stop signal can be sent directly to brakes without passing through the controller, thus improving the reliability of the system by reducing the risks of electronic components failure. Once the robot is stopped, gravity tends to naturally return the mechanism to its original position. One important advantage of the parallelogram architecture is that the couple passing through the torque limiter only depends on the magnitude of the horizontal force applied on the end-effector and *is not affected by the height of the point of application of the force*. This implies that the same force level will cause the activation of the safety mechanism whether the collision occurs at the head or at the knee of the person. This is an important advantage since a collision can occur anywhere on the end-effector.



(a) Before collision (b) Collision (c) After collision

Fig. 1. Example of a 1-DOF Cartesian FLD using torque limiters(©2009 IEEE).

In Lauzier et al. (2009), this simple 1-DOF architecture was extended to a 2-DOF mechanism that reacts to collisions occuring in the whole horizontal plane. It is also possible to extend it to 3-DOF, thus covering all possible collisions occuring on the end-effector. For example, the Delta architecture can be used to create a 3-DOF CFLD by replacing the actuators with torque limiters, as shown in Fig. 2. However, since the mechanism is sensitive to vertical forces, the end-effector's weight (plus the carried load) will induce articular torques that will limit the robot's ability to apply forces before reaching its threshold. To circumvent this problem, the device has to be statically balanced.

Experiments were performed using a reduced-scale prototype of a 2-DOF CFLD to evaluate the behaviour of such a device during a collision. Fig. 3 shows the experimental setup and the contact force over time for a collision occuring at a low velocity. On the graph, it is possible to see that the contact force is slowly increasing until it reaches the preset threshold, after which it drops sharply to a level corresponding to the friction force until the motion is stopped. This shows that for collisions occuring at a low velocity, the maximum contact force is approximately limited to the preset threshold. For higher velocities, the inertia of the end-effector and the stiffness of the contact interface must be taken into account. More detailed results are presented in Lauzier et al. (2009).

3.1 Safety Improvements

It is important to evaluate the safety improvements and the limitations of the proposed approach which consists in placing a mechanism on the robot that can disconnect the end-effector if the forces applied on it are excessive.

Firstly, in the case of mechanisms performing horizontal motion only, the load to be carried by the robot is not limited. This is also the case for the 3-DOF architectures if gravity is compen-

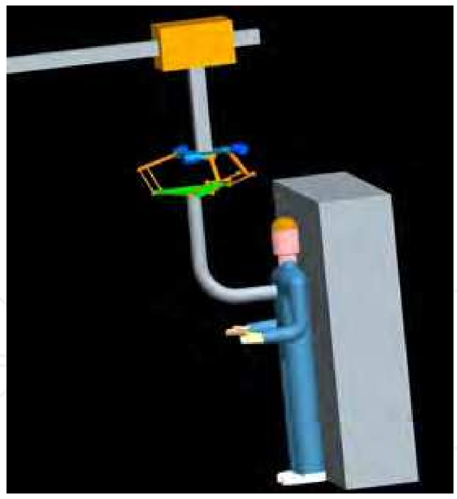


Fig. 2. Example of a collision between a person and a suspended robot with a 3-DOF CFLD using Delta architecture.

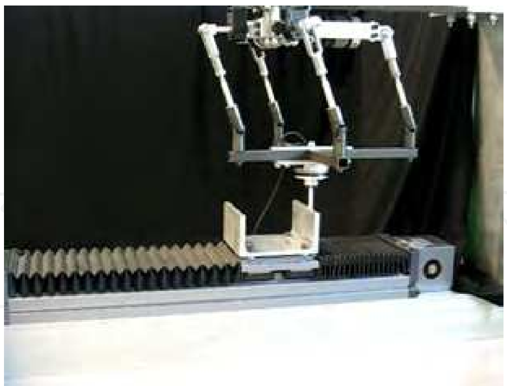
sated for. However, accelerations of the robot will induce inertial forces that can activate the torque limiters of the mechanism. Thus, for a given load, accelerations must be limited to a certain level to prevent the end-effector from being disconnected without collisions. This is a potential disadvantage because a robot usually aims at maximizing accelerations/decelerations. Secondly, there is always a maximum velocity that can be imposed to a robot that will ensure that blunt, unconstrained collisions will be safe. This "safe" velocity is usually very low for heavy robots. However, if during a collision the end-effector is disconnected from the robot, the effective inertia to which the person is subjected is then greatly reduced. Therefore, it can be assumed that using this type of mechanism will allow to increase the maximum velocity of a robot moving around people. This maximum velocity should be evaluated using a collision model that considers all collision parameters, including the way the robot reacts when the collision is detected (braking force, delay before the brakes are applied, etc.).

Thirdly, as explained in Haddadin, Albu-Schaffer, Frommberger & Hirzinger (2008), collisions in which a human body is clamped to a wall by a robot can be very dangerous. With the mechanism described in this paper, however, the maximum clamping force that the robot can apply in quasistatic conditions is determined by the limit torques of the limiters. As the velocity increases, the safety is still improved because the inertia crushing the person's body against the wall is reduced. Again, the maximum velocity should be calculated using an appropriate model to ensure safety.

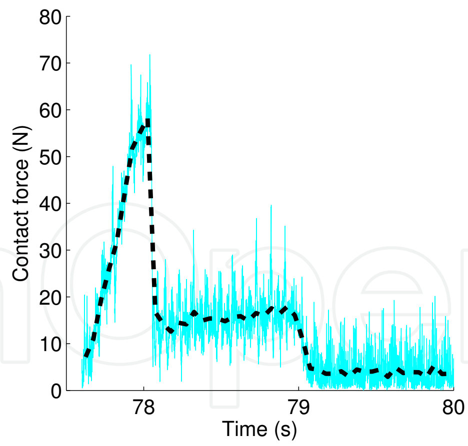
Also, because the mechanism is unable to store elastic potential energy (as opposed to compliant robots), it will not make the robot continue pushing on the person's body after the collision has taken place. This is an advantage since it will help the person to push the robot away after the collision.

Advantages over Existing Devices

Some robots designed for pHRI, such as the Kuka KR3-SI Haddadin, Albu-Schaffer & Hirzinger (2008), incorporate a flexible flange with breakaway function that links the tool to the manipulator. This device triggers an emergency stop when the contact force at the tool control point exceeds a certain threshold. Although this type of device behaves similarly on many aspects to the devices described in this section, it differs on certain points. Firstly, it lim-



(a) Experimental setup(©2009 IEEE).



(b) Force over time for a low velocity collision(©2009 IEEE).

Fig. 3. Experimental collision between a 2-DOF CFLD prototype mounted on a structure and a linear actuator.

its the moment – not the force – that can be transmitted by the manipulator to the end-effector. This means that the threshold depends on the location of the collision point, as opposed to the proposed Cartesian FLDs. The latter behaviour is preferable since a collision can generally occur anywhere on the end-effector. Also, the proposed mechanism has a large achievable displacement compared to the existing device. This is an advantage since it yields the space required by a heavy ceiling mounted manipulator to stop without crushing the person involved in the collision.

4. Robot Soft Covering

The key idea behind compliant joints is to reduce the peak force attained during a collision. Covering a robot with a soft material can provide a very similar feature by absorbing directly the collision energy. However, since this safety element is an external cover, therefore isolated from the internal forces given by the robot dynamics, this approach does not suffer from the same drawback as compliant joints. Indeed, in this case the compliance has no effect on the robot end-effector stiffness and thus no tradeoff has to be made between the ideal compliance required for safety and minimum wanted robot stiffness. This characteristic gives to the robot designer a total freedom in the choice of the compliance.

This approach does not only have advantages. The thickness of the covering material required for attaining a good level of safety could be relatively large as mentioned in Zinn, Khatib, Roth & Salisbury (2004b). This extra material could significantly increased the weight of the robot with a negative impact on its dynamics performance . Fig. 4 shows some collision tests that have been presented in Duchaine, Lauzier, Lacasse, Baril & Gosselin (2009). From these curves it is possible to observe that with the 3 mm thick sample tested, even if the soft cover has a measurable impact in reducing the collision peak forces, this reduction is not enough to make the robot safe. The data of collision peak force for the case where the soft covering can provide sensing to detect contact is also provided. In this case the reduction is drastic and the robot is easily in the safe zone. This latter approach that combines soft covering and active sensing is often referred to robot skin. This concept is a promising solution that could

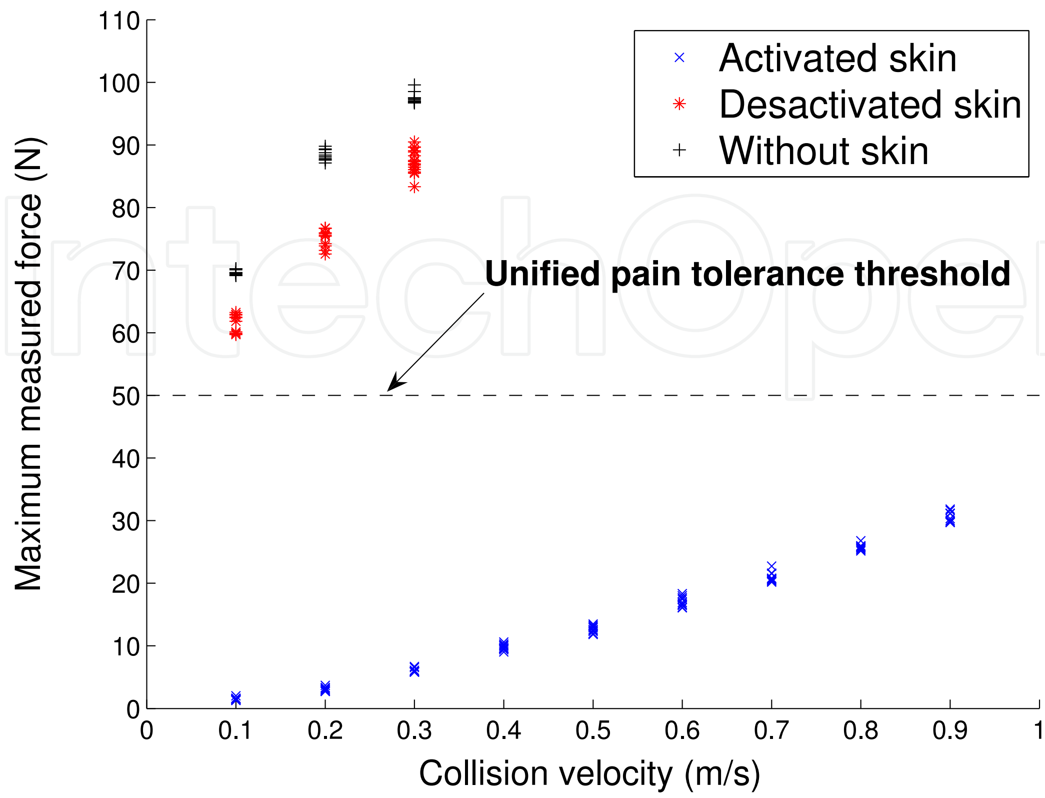


Fig. 4. Maximum force measured for different collision velocities. (©2009 IEEE)

become a *must have* feature on the next generation of cooperative robots. However, so far there is no commercially available robot skin on the market and there is still many research challenges associated to this topic such as manufacturing, wire routing and post processing of the signals. An interesting review of the state of the art in this area and an overview of the remaining challenges is presented in Cutkosky et al. (2008).

5. Efficient Joint Actuation Coupling

Conventional serial manipulators typically have one motor attached at each joint, thus leading to a direct relationship between the vectors of actuation torque (τ_m) and the joint torque (τ). In the design of such robots, each actuator is chosen so that it has the capability to deliver the maximum torque required at its associated joint. One way to improve safety in pHRI is by coupling the actuation of some of these joints. Indeed, actuation coupling for some very specific robot architectures could lead to a significant reduction of the maximum force that the robot can apply to a human being in the case of a malfunction or an unwanted contact. The capability of a robot to apply forces to its environment is maximized when the robot is in an equilibrium configuration, i.e., when no joint torque is required to maintain its pose. In such a configuration and for a short period of time, all the available torque can be directly used to apply forces to the surrounding environment. Reducing this maximum torque while maintaining the same static capability could greatly enhance the overall safety of a robot without affecting its performances.

i	θ_i	α_i	a_i	b_i
1	θ_1	$\frac{\pi}{2}$	0	l_1
2	θ_2	0	l_2	0

Table 1. HD parameters of the robot of figure 5.

For a general manipulator with a direct relationship between joint torque and actuator torque as described above, the maximum torque at each joint can happen independently from the others, therefore, one has:

$$\max(\tau_i + \tau_j) = \max(\tau_i) + \max(\tau_j), \quad \forall i, j \tag{1}$$

where τ_i is the ith joint torque. In this case, coupling the actuation of the joints will not lead to a significant improvement since instead of requiring two actuators with a maximum torque capability of τ we will end up with one more powerful actuator that can supply a torque of 2τ. However, for some specific serial architectures, it can be observed that eq. (1) becomes:

$$\max(\tau_i + \tau_j) < \max(\tau_i) + \max(\tau_j). \tag{2}$$

This equation means that, for this architecture, the maximum torque at each joint is not independent from the others and that the maxima cannot happen simultaneously. This kind of architecture can lead to what we call *efficient joint actuation coupling*. One good example of such an architecture is the human arm, where the largest muscle, the biceps, is involved in the upperarm supination as well as in the forearm extension.
The intent of this section is not to show how to mechanically achieve efficient joint *actuation* coupling but to demonstrate the potential contribution of this concept to safe pHRI and to illustrate how the joints to be coupled can be selected in order to maximize the benefits. Indeed, among all the possible joint arrangements in a serial robot, very few combinations will lead to a beneficial actuation coupling. Therefore, some design guidelines to achieve such coupling will be given by finding the corresponding constraints on the Denavit-Hartenberg (D-H) parameters.

5.1 Constraints on the Denavit-Hartenberg Parameters to Achieve Efficient Joint actuation Coupling

In this section, conditions on the Denavit-Hartenberg (D-H) parameters are derived that lead to a serial arrangement providing an efficient coupling of two of its joints. The conditions obtained are sufficient to satisfy eq. 2 but they may not be necessary. In other words, there is no proof yet that these conditions are the only possible combinations of D-H parameters that satisfy eq. 2.

5.1.1 Two-Degree-of-Freedom Serial Architecture

One simple architecture that leads to an efficient coupling is a two-dof serial combination of revolute joints with the D-H parameters given in Table (1). In this table, θ_i is used to denote the ith joint variable, α_i is the twist, a_i is the length and b_i the offset. A schematic representation of the corresponding robot is given in fig. 5. By observation of the figure, it is possible to observe that the maximum static torque at each joint cannot occur simultaneously for this serial arrangement. Using the expression of the corresponding joint torques helps understanding the reasons behind this behaviour.

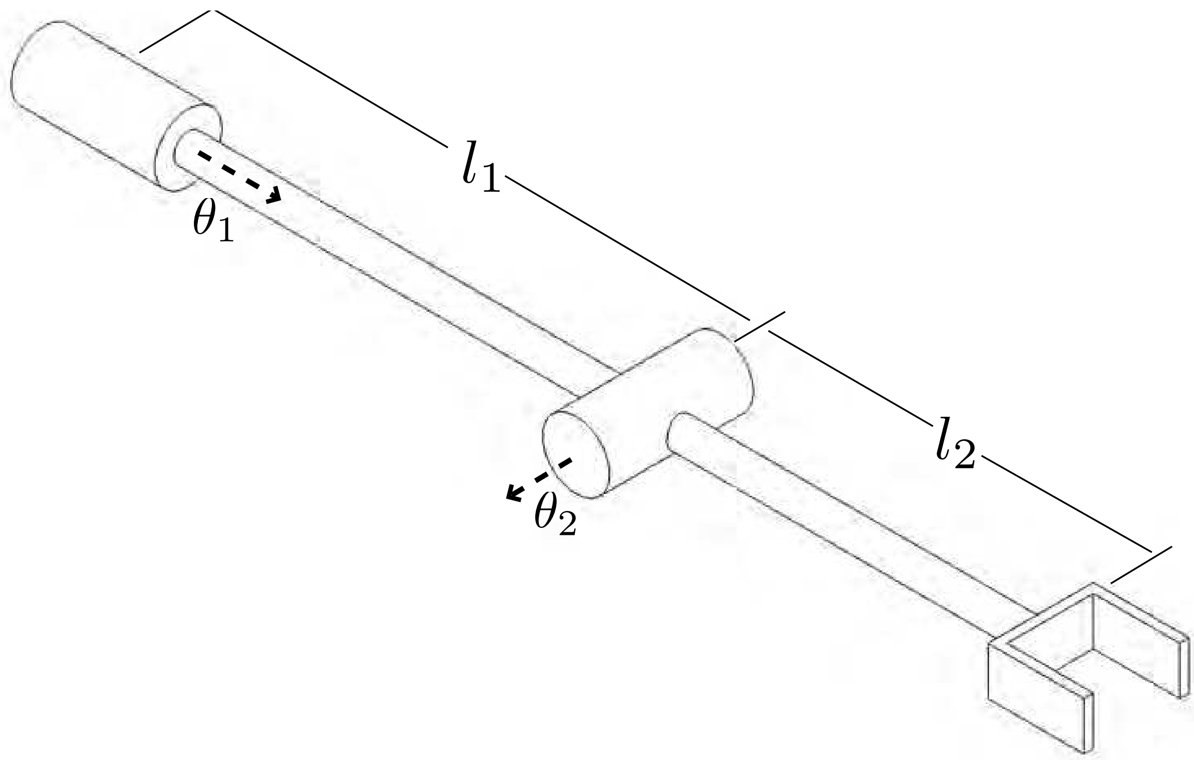


Fig. 5. Two dof serial architecture.

As suggested in the ANSI/RIA R15.06-1999 Standard for robot safety in factories, the maximum acceleration and velocity of a robot is typically low in the context of pHRI. Therefore, The maximum torque needed at each joint can be roughly estimated from the static forces, i.e., from the effect of gravity on the robot and its payload. The mathematical expressions for the torque induced by gravity at each joint of the robot of fig. 5 are given by:

$$\tau_1 = \frac{\partial V}{\partial \theta_1} = \frac{m_2 g l_2}{2} \cos\theta_1 \cos\theta_2 \tag{3}$$

$$\tau_2 = \frac{\partial V}{\partial \theta_2} = \frac{m_2 g l_2}{2} \sin\theta_1 \sin\theta_2, \tag{4}$$

where V is the gravitational potential energy given by

$$V = V(\boldsymbol{\theta}) = \sum_{i=1}^{n} m_i g h_i, \tag{5}$$

in which m_i is the mass of the ith member, g the gravitational acceleration, h_i the elevation of the centre of mass of the ith member measured from a fixed reference and n is the total number of links. In order to verify if this architecture can lead to efficient coupling by satisfying eq. (2), the sum of the joint torques is computed, namely:

$$\tau_1 + \tau_2 = \frac{m_2 g l_2}{2} \cos\theta_1 \cos\theta_2 + \frac{m_2 g l_2}{2} \sin\theta_1 \sin\theta_2. \tag{6}$$

Using the following trigonometric identity:

$$\cos(a \pm b) = \cos a \cos b \mp \sin a \sin b, \tag{7}$$

eq. (6) can be reduced to:

$$\tau_1 + \tau_2 = \frac{m_2 g l_2}{2} \cos(\theta_1 - \theta_2). \quad (8)$$

Therefore, since:

$$\max(\cos a) = \max(\sin a) = \max(\cos(\mathrm{a} + \mathrm{b} + ...)) = 1, \quad (9)$$

we obtain:

$$\max(\tau_1 + \tau_2) = \max(\tau_1) = \max(\tau_2) = \frac{m_2 g l_2}{2}. \quad (10)$$

This result is the minimum possible value for eq. 2, which means that it could be possible, with appropriate coupling, to drive these two joints with only one of the two motors. The key to this reduction lies in the fact that the sine and cosine expressions for the individual joint torques, when added together, can be combined into another cosine function by virtue of the trigonometric identity of eq. (7).

5.1.2 Generalization

The architecture described above is one possible example of application of efficient joint actuation coupling. However, it is important to generalize the results in order to determine all the possible serial architectures that can lead to efficient joint actuation coupling. One way to proceed is by finding the constraints on the DH parameters that allow the satisfaction of eq. (2).

For a 2-dof architecture, the expression of the joint static torques for a general value of the DH-parameters can be written as:

$$\tau_1 = \frac{1}{2} a_2 \cos\theta_1 \cos\theta_2 - \frac{1}{2} a_2 \cos\alpha_1 \sin\theta_1 \sin\theta_2 + \frac{1}{2} b_2 \sin\alpha_1 \sin\theta 1 \quad (11)$$

$$\tau_2 = -\frac{1}{2} a_2 \sin\theta_1 \sin\theta_2 + \frac{1}{2} a_2 \cos\alpha_1 \cos\theta_1 \cos\theta_2. \quad (12)$$

As demonstrated above, the trigonometric indentity of eq. (7) is the key that led to eq. (10). In order to make it possible for the sum of eqs. (11) and (12) to be manipulated using this trigonometric identity, the following constraints need to be introduced:

$$\cos\alpha_1 = b_2 \sin\alpha_1 = 0 \quad (13)$$

and

$$a_2 \neq 0 \quad (14)$$

This imposes the following constraints on the DH-parameters:

$$\alpha_1 = (2n+1)\frac{\pi}{2} \quad (15)$$

$$b_2 = 0 \quad (16)$$

where n is any integer.

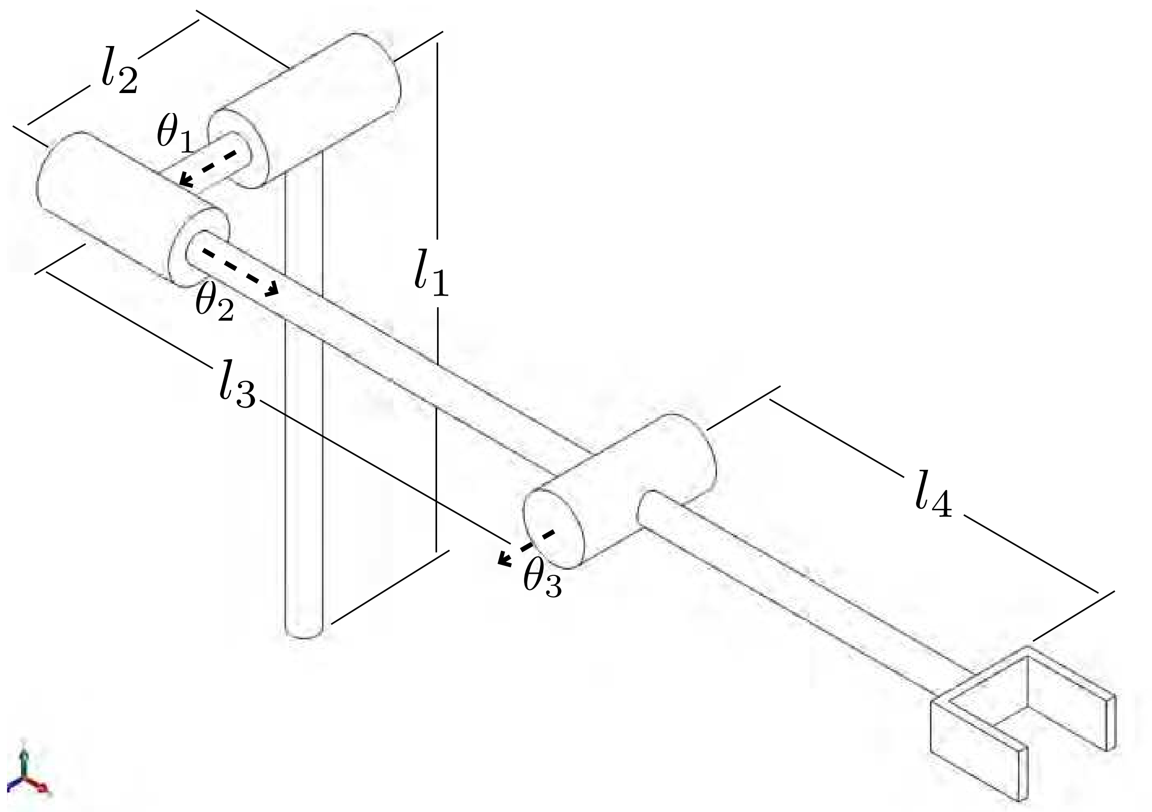


Fig. 6. Three *dof* serial architecture.

i	θ_i	α_i	a_i	b_i
1	θ_1	$\frac{\pi}{2}$	0	l_1
2	θ_2	$\frac{\pi}{2}$	0	l_2
3	θ_3	0	l_3	0

Table 2. HD parameters of the robot of figure 6.

5.1.3 Three-Degree-of-Freedom Serial Architecture

The previous example is rather trivial since the first member of the robot is fixed relative to the direction of gravity. In order to obtain a more realistic situation, a three-dof architecture is now considered. Table (2) provides the HD-parameters of the chosen architecture, which is illustrated schematically in fig. (6). The possible coupling of the last two joints is investigated. Computing the static forces from the potential energy as in eq. (5), the sum of the gravity torques of the last two joints of this serial architecture can be written as:

$$\tau_2 + \tau_3 = \frac{m_2 g l_2}{2} \left(\sin\theta_1 \sin\theta_2 \cos\theta_3 + \sin\theta_1 \cos\theta_2 \sin\theta_3 + \cos\theta_1 \cos\theta_3 \right). \tag{17}$$

The trigonometric identity of eq. (8) is now used, together with the following identity:

$$\sin(a \pm b) = \sin a \cos b \pm \cos a \sin b \tag{18}$$

and eq. (17) can then be reduced to

$$\tau_2 + \tau_3 = \frac{m_2 g l_2}{2} \left(\sin\theta_1 \sin(\theta_2 + \theta_3) + \cos\theta_1 \cos\theta_3 \right). \tag{19}$$

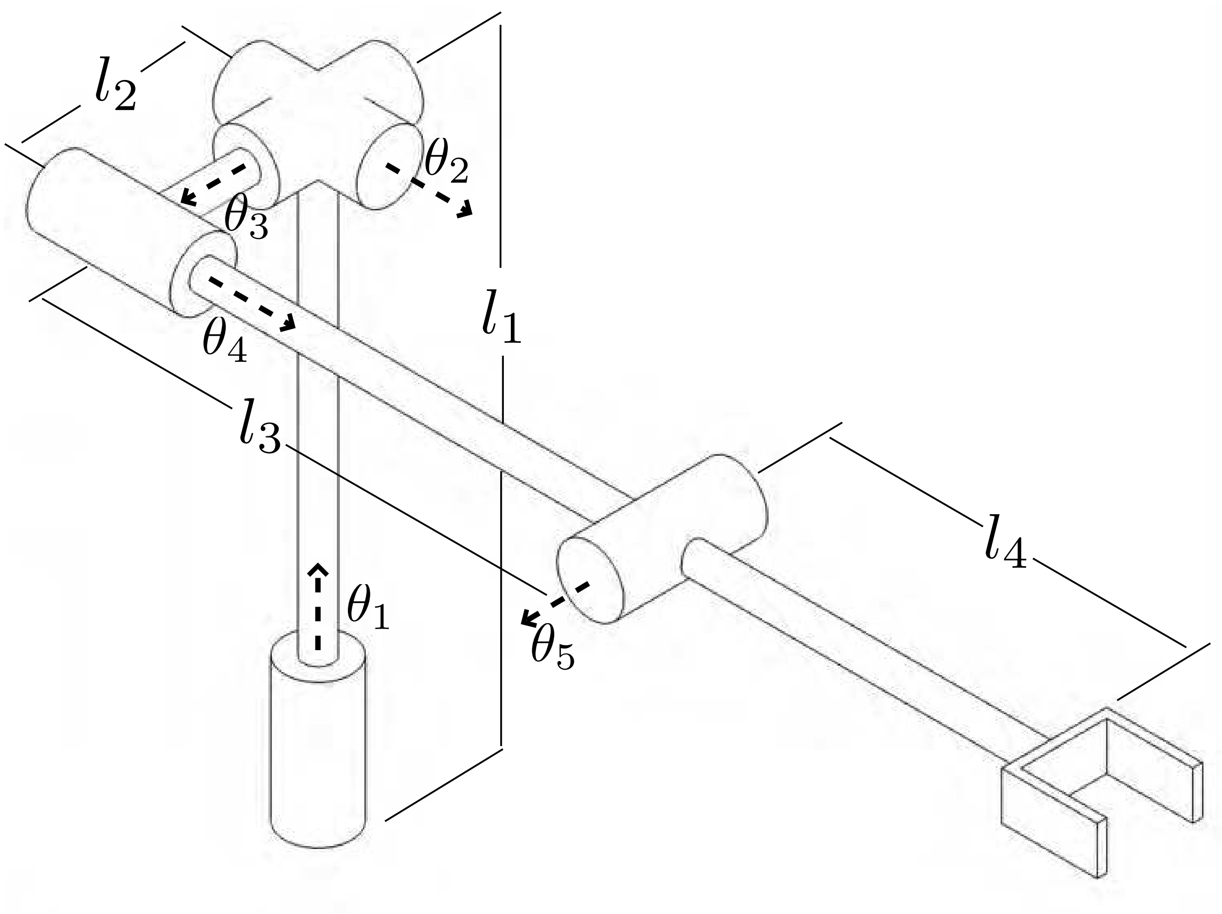


Fig. 7. Five dof serial architecture.

The maximum value of this expression can be obtained as:

$$\max(\tau_2 + \tau_3) = \frac{m_2 g l_2}{2} \max\left(\sin\theta_1 \sin(\theta_2 + \theta_3) + \cos\theta_1 \cos\theta_3\right) \quad (20)$$

$$= \frac{m_2 g l_2}{2} \max\left(\sin`_1 + \cos`_1\right) \quad (21)$$

$$= \frac{\sqrt{2}}{2} m_2 g l_2 \quad (22)$$

and therefore

$$\max(\tau_2 + \tau_3) = \sqrt{2}\max(\tau_2) = \sqrt{2}\max(\tau_3). \quad (23)$$

In this case, the gravity torque cannot be perfectly combined and it will not be possible to drive both joints with a motor that would have been selected for driving only one of the joints. However eq. (23) still satisfies eq. (2), meaning that combining the motion of both joints will require significantly less torque than driving both separately.
If the above exercise is repeated with three orghogonal revolute joints prior to the last two members, then the latter can have any possible orientation with respect to gravity. One then

obtains:

$$\tau_4 + \tau_5 = \frac{m_5 g l_5}{2} (\sin\theta_2 \cos\theta_3 \sin(\theta_4 + \theta_5) + \cos\theta_2 \cos(\theta_4 + \theta_5) - \sin\theta_2 \sin\theta_3 \cos\theta_5) \quad (24)$$

and the maximum for the sum of the torques is again given as

$$\max(\tau_4 + \tau_5) = \frac{\sqrt{2}}{2} m_5 g l_5 = \sqrt{2}\max(\tau_4) = \sqrt{2}\max(\tau_5). \quad (25)$$

Figure (7) provides a schematic illustration of such an architecture. Since this architecture allows all possible orientations of the member of length l_3, it is possible to make a generalization of the results. Therefore, if the HD parameters associated with the last two dofs of the manipulator satisfy the constraints given by eqs. (15) and (16), no matter what will be the prior serial arrangement, coupling the actuation of the last two dofs will result in a significant reduction of the maximal torque compared to separate actuation.
If the designer wants to add other dofs after the member of length l_4 of the architecture presented in figure (7), eq. (25) will no longer be true. However, if all a_i and b_i for $i > 5$ in the HD parameters are kept as small as possible relative to the length of l_4, or if the centre of mass of these extra dofs are close to the end of l_4 or if the extra links are light, the gain can still be significant. The human arm is a good example of this situation, with is maximum reach mainly given by the upper arm(l_3) and the forearm (l_4).

6. Conclusion

Human-robot interaction is the next logical step in the evolution of robotics. However, the challenge of bringing robots in our environment is not simply about increasing their capabilities and their functionalities. Even before that, robots need to be built in a way that they cannot hurt human beings. In this chapter, we have reviewed several concepts that have been proposed in the recent years in order to address this particular challenge. The popular idea of compliant joints was exposed from Series Elastic Actuators (SEA) to the distributed Macro-Mini concept (DM2). A special emphasis was placed on the recent concept of Force Limiting Device (FLD), which we believe circumvents some of the drawbacks associated with compliant joints. We have also presented the concept of external compliance via soft covering of the robot. Finally, a new concept of efficient joint actuation coupling was proposed to reduce the capability of a robot to transfer energy to its environment while maintaining the same dynamic performances.

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Robot manipulators are developing more in the direction of industrial robots than of human workers. Recently, the applications of robot manipulators are spreading their focus, for example Da Vinci as a medical robot, ASIMO as a humanoid robot and so on. There are many research topics within the field of robot manipulators, e.g. motion planning, cooperation with a human, and fusion with external sensors like vision, haptic and force, etc. Moreover, these include both technical problems in the industry and theoretical problems in the academic fields. This book is a collection of papers presenting the latest research issues from around the world.